Hardware Implementation of Cryo-Pneumatic Engine Control Unit

Sruthi Rajan
Dept. of ECE
Sree Buddha College of Engineering
Kerala, India.
sruthirajan90@gmail.com

Padmakumar K, Anupama L,
Dominic George Joseph,
Saji K Jose, Anna Priya Koshy,
Flight Computers Division,
VSSC,ISRO
Thiruvananthapuram.

AthiraShaji
Asst. Prof., Dept. of ECE
Sree Buddha College of Engineering
Kerala, India.
athirashaji@gmail.com

***Abstract*—Pressure is an important parameter which affects the performance of the cryogenic engine. This paper presents the hardware implementation of Cryo-Pneumatic Engine Control Unit (ECU). When the liquid hydrogen (LH2) or liquid oxygen (LOX) tank pressure exceeds a specified limit, catastrophic failure may occur and when below a specified limit, the normal working of the launch vehicle is interrupted. The pressures of the tanks are maintained within safety limits through the implementation of cryo-pnuemo hydraulic algorithms, namely venting algorithm and isolation algorithm. This paper presents the idea of reducing the computational complexity of the processor for implementation of the algorithms, by offloading the processor and putting the logic in an FPGA. This result in reduction of memory usage, processor complexity, clock rate, and communication channel congestion. This also provides more computational margin. The paper describes the implementation of ECU onto a Xilinx based Virtex 5 FPGA platform.**

***Keywords*—cryogenic, embedded system, engine control unit, FPGA, pressurization, isolation, venting.**

I. Introduction

EMBEDDED system is becoming wide spread in all industries. Embedded system co-design is a major challenge faced by the design engineers. Co-design is the careful planning of dividing the tasks between hardware and software such that all the available resources are effectively utilized[1]. The launch vehicle is controlled in hard real time where a hard real time task should always meet the performance deadlines. The choice of hardware [2] is important in this aspect and hence implementation in hardware is an effective solution to meet deadlines. To get the advantage of both hardware and software, partitioning the task between hardware and software is done. Cryogenic stage operations include providing proper pressurization to and isolation between command gas bottle (CGB) and pressurization gas bottle (PGB).

This paper tries to implement the venting algorithm and isolation algorithm on hardware. The proposed method improves the execution time of the processor thereby giving more room for other critical real time tasks.

The section II of the paper gives an overview about the structure of the cryogenic engine and the background of the project. Section III disucess the design of the ECU. It explains the hardware followed by the module wise block diagram of the ECU. The state machines implemented used are also discussed subsequently. Section IV disusses the results obtained from the implementation and finally, section V discusses the conclusion drawn from the implentation.

II. Cryogenic Engine

The cryogenic rocket engine described here uses cryogenic liquid hydrogen (LH2) fuel and the liquid oxygen (LOX) oxidizer [3]. The pressure regulation of LOX and LH2 is mission critical. The structure of cryogenic engine is shown in Fig 1.

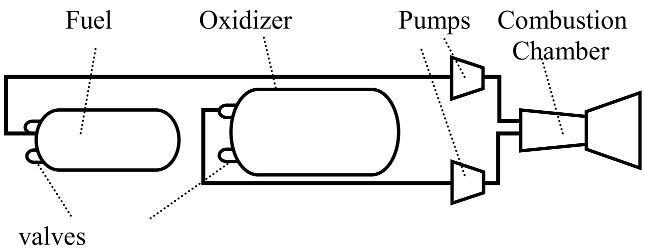

Fig 1: Structure of cryogenic engine.

A. Why Engine Control Unit?

As the launch vehicle enters into different layers of the atmosphere, the atmospheric pressure/temperature causes the pressure inside the tanks to vary drastically and pressure inside the tanks may fall below safe limits. Hence constant monitoring of pressure and maintaining of pressure within the permissible limit should be done. So the requirement of the system is to ensure a minimum pressure above the vapour pressure at the inlet to the pumping system. The venting of tanks ensures proper pressure maintenance of the system. This operation is carried out by venting algorithms.

The fuel to tanks is supplied from large reservoirs known as gas bottles. The gas bottles need to hold large amount of gas at high pressure. If the volume of the gas bottle is large the

pressure it can deliver is less. To compensate this the gas bottles have two chambers, command gas bottle (CGB) and pressurization gas bottle (PGB) respectively. CGB and PGB are connected through a pyro valve. Normally the pyro valve is open to provide large volume. CGB is for keeping the electro pneumatic valve (EPV) intact and the PGB for pressurisation of the tank. The CGB pressure should always be greater than a specific value. When the pressure falls below this specific value then the valves are closed to provide isolation. Hence the isolation algorithm provides the isolation between CGB and PGB.

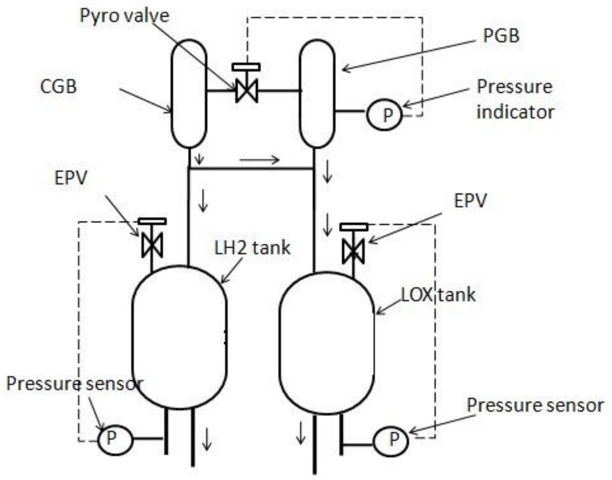

Fig 2: Environment for ECU.

The fig 2 shows the structure along with the control for the implementation of both venting and isolation algorithms [4]. The pressure of the tank is obtained from the pressure sensors and accordingly the electro pneumatic valve iscontrolled to let the excess pressure out of the tank. The command gas bottle and pressurization gas bottle are connected by a pyro valve as shown in figure.

B. Related works:

Engine control was earlier a part of the main computer of the launch vehicle. It implements both the venting and isolation algorithm on software. The sensors sense the pressure in the tanks and send this data to the processor upon its request. The dedicated processor implements both the algorithms and sends back the output command to the valve for controlling the tanks. The communication is established through MIL STD 1553 protocol. The processor acquires the inputs from the sensors through request command and sends back the output to valves through response command. The processor does the entire cryogenic operations. This is an additional overhead on the processor and makes the MIL STD 1553 protocol communication complicated.

III. DESIGN AND IMPLEMENTATION

The advantage of decentralized FPGA implementation of the algorithm is that the processor overhead can be reduced and processor could do other time critical tasks. The proposed method reduces the usage of 1553 protocol also [6][7]. The method of hardware implementation use the protocol just for the communication of the sequence commands to the ECU and carry the status back. The hardware implementation reduces the data transfer requirement.

A. Hardware:

The ECU system includes pressure sensors, FPGA, 1553 bus and processor. Fig 3 shows the hardware of the ECU system.

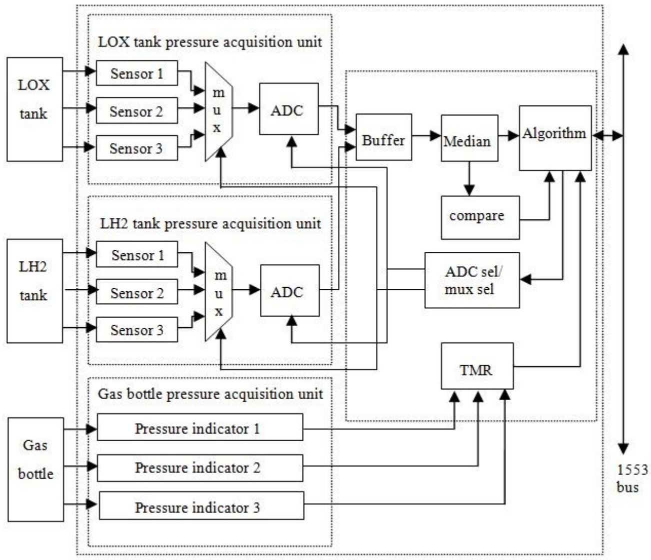

Fig 3: Hardware of ECU system.

The Acquisition unit acquires pressure from the sensors in the walls of the tanks. The proposed system is an engine pressure control unit. It is an FPGA implementation of acquisition unit and processing unit. The controlling parameter is the pressure of the tanks and the gas bottles. Sensors acquire pressure from tanks and give it to the FPGA and the control output from FPGA is directly issued to the engine to control the pressure.

B. Block Diagram:

The block diagram of the engine control unit consists of acquisition module, timing module, synchronization module, encoder-decoder module, algorithm module and error handling module. The Fig 4 shows the block diagram of the ECU.

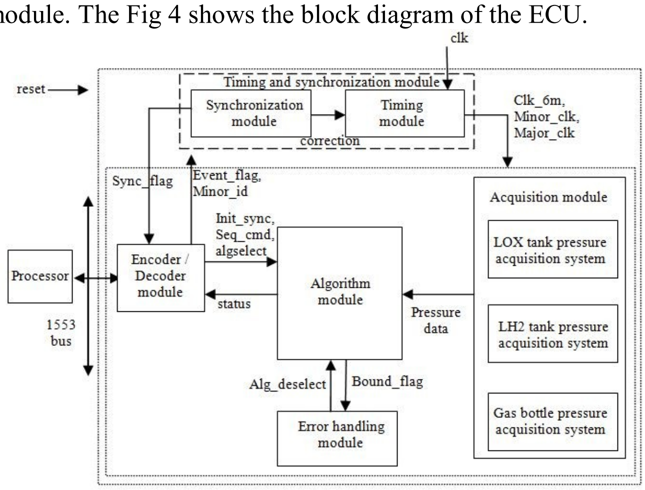

Fig 4: Block diagram of ECU.

This unit vents out the excess pressure from the LOX and LH2 tanks by opening the electro pneumatic valve (EPV) thus

keeping the pressure within the normal permissible limit. This is achieved through the venting algorithm. The same helps in closing the valve when the pressure falls below the normal level. The unit is also responsible for pressurizing the tanks in the initial stage. The pressurisation from the gas bottle is also controlled by this unit. The pyro valve is closed and isolation is provided when pressure inthe gas bottle falls below the limit

All the modules are designed using state machine modelling in VHDL. Functional descriptions of each module are as follows:

1) *Timing module*: This module takes the input clock and generates the required encoder clock, minor clock and major clock which is used by other sub modules.

2) *Synchronization module*: This module provides the timing synchronization with the processor.

3) *Acquisition module*: This module acquires pressure input from the sensors mounted on the walls of the tanks. The obtained pressure is processed with help of special hardware and stored in a register. The acquisition module consists of LOX Tank pressure acquisition system, LH2 Tank pressure acquisition system and Gas Bottle pressure acquisition system.

The state machine is used for the acquisition of data and generation of required control signals (ADC and mux selection signals). The module uses a mux and ADC to acquire pressure data from the tanks. The averages of 8 samples are taken for assuring the integrity of the acquired data. The data is then stored so that it can be used by the algorithm module for pressure data processing. Fig 5 shows the state machine for acquisition module.

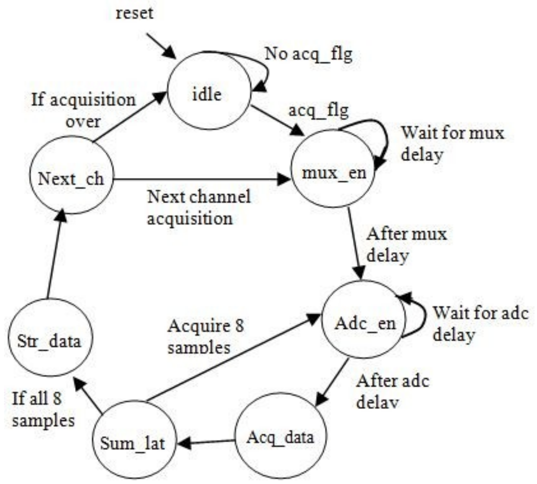

Fig 5: State machine for acquisition module.

4) *Algorithm module*: This module computes the venting and isolation algorithm. The venting and isolation is done as per the pressure limit requirements of the system. The engine control unit executes the algorithms which command the electro pneumatic valves/ the pyro valve. The excess pressure is expelled out through the venting action.The Gas bottle is at a pressure of $22x10^6$ Pa which controls the pressurization of both LOX and LH2 tanks. The tank LH2 is operated in the regulated mode. The primary function of PGB is to provide pressure to both tanks. The CGB keeps the valve intact which needs a minimum of $5x10^6$Pa. So the isolation threshold of $8x10^6$ Pa is kept. The entire life span of the single operation of the algorithm falls within the major cycle duration. The major cycle has a period of 500 ms which is divided into 25 minor cycles. The venting and isolation is done if the pressure condition satisfies for the first 3 consecutive minor cycles of each major cycle. The pressure data shall be used in the algorithm only in the first three minor cycles of each major cycle. Fig 6 shows the clock cycle for ECU.

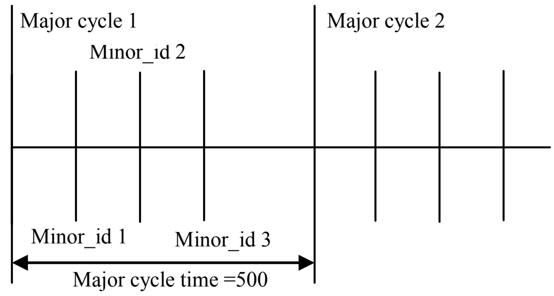

Fig 6 Clock cycle for ECU.

The Algorithms are as follows:

a) Venting algorithms:

Algorithm A:

Venting action of LOX tank is achieved through Algorithm A. Algorithm A operates in only one mode. Whenever Algorithm A*mode off* command is issued, the algorithm should stop its execution after closing EPV 186. Close command is also issued when the valve remains open for control period duration.

Algorithm C:

In case of LH2 tank, due to the property of self evaporation the pressure in the tank varies drastically. To compensate this variation in pressure, algorithm C operates in two modes. The modes differ only in the value of pressure limits. Whenever mode command is issued by processor then the algorithm C goes to corresponding mode ofoperation. In both the modes, when the pressure exceeds upper limit, the excess pressure is vented out by opening the EPV. When the pressure falls below lower limit, then pressure in the LH2 tank is to be maintained by closing EPV.

During the execution in any of the modes, if the Algorithm C *mode off* command (mode0) is received, then the algorithm should terminate its execution after closing the EPVin that minor cycle itself. Close command is also issued when the valve remains open for control period duration.If mode change command is received within the first three minor cycles of a major cycle, then it is recognized and EPV is closed immediately, in that minor cycle itself. Otherwise, EPV will be closed in the next major cycle.

Venting algorithm is executed as two parallel processes, pre-processing and processing.

- *Pre-processing (Selection):*

The median of the three pressure data obtained from the acquisition module is computed using median logic (see fig 7). The bound check for the computed median value is then done. The bound check flag indicating the success of the bound check is used for selecting the pressure value for algorithm processing. The pre-processing starts as soon as the flight reset is received.

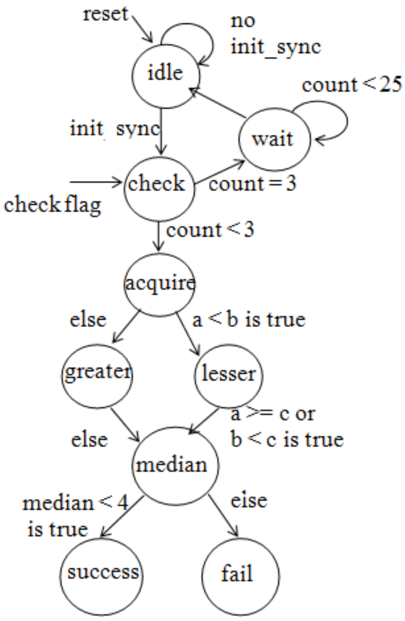

Fig 7: State machine for venting algorithm selection.

- Processing :

The algorithm is invoked when the sequence command is received. The selected pressure data is checked with the tank upper and lower bound and decision for opening and closing of valve is taken accordingly.

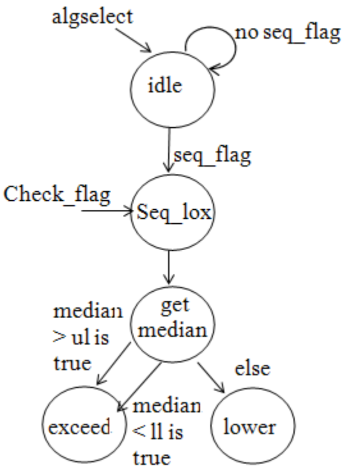

Fig 8: State machine for Algorithm A processing

Bound check failure is indicated through bound error counter. The open command is issued based on the pressure values from the sensors. The failure in the sensors result in the incorrect data being delivered to the algorithm. This results in the opening of the valve for an indeterminate period of time. This may lead to the lowering of pressure in the tank below the specified limit. Thus the integrity of the data from sensors is an important factor which is ensured through the control period (T). This is acheived by closing the valve forcibly after the control time (T). This avoids the chance of venting out the pressure for indeterminate period of time. Fig 8 shows the state machine for algorithm A processing and Fig 9 for algorithm C processing.

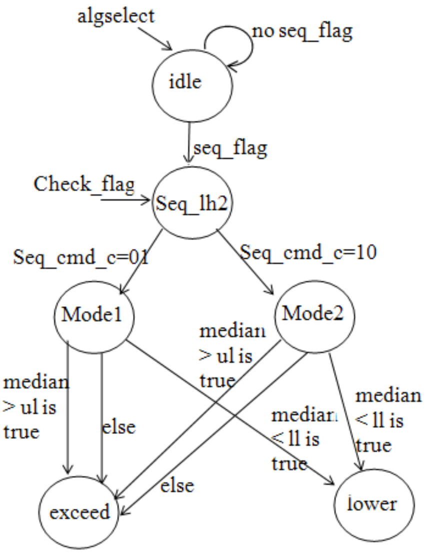

Fig 9: State machine for Algorithm C processing.

b) Isolation Algorithm:

Algorithm K

Algorithm K isolates the pressurization gas bottle (PGB) and command gas bottle (CGB) when the gas pressure falls below $8x10^6$ Pa. Pyro valve is a normally open valve, when fired it closes isolating the CGB and PGB.Algorithm K is to isolate the CGB and PGB when the combined pressure level falls below the specified value or when sequencing command is issued at the default time, whichever is earlier (see fig 10).

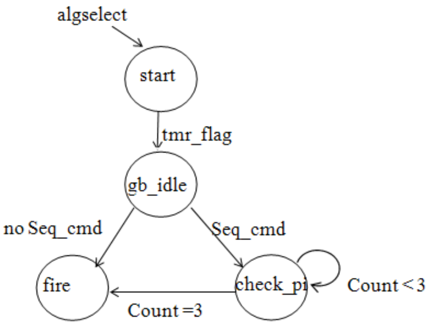

Fig 10: state machine for Algorithm K.

Algorithm K is executed as two parallel processes:

- Pre-processing (selection) : The TMR logic of the three pressure indicators obtained from acquisition module is computed.
- Processing : The pressure indicator is checked for its status. If status is open for the first three consecutive minor cycles then command is issued to fire the pyro valve to close it.

5) *Error handling module* : Error handling is initiated when the bound check fail continues for '28' consecutive cycles. The error is reported back to the processor through the error counters. Upon the error detection corresponding algorithm is deselected. Before deselecting the corresponding valves are closed and algorithm enters disabled state.

6) *Encoder decoder module* : The module contains Manchester encoder and decoder logic.

C. Implementation:

1) *Hardware Requirements*:
Xilinx Virtex 5 FPGA, SAR AD7876 and HI 506 single 16 channel multiplexer.

2) Other Requirements:
Check-out system : RT-Linux based check-out system for simulating control command.
Hardware in-loop configuration : Processor based avionics configuration based on 1553.

IV. RESULTS

The designed Engine Control Unit has been simulated using ModelSim. The simulation result is shown in fig 11. The proposed system has successfully met all the specified requirements. The proposed method reduces the overhead in the processor by freeing it to do other tasks. The offloading of processor by 2 ms per 20 ms (minor clock) was achieved. The improvement of 200 µs in communication bandwidth of 1553 protocol was also acheived. Then the design is synthesized using Xilinx ISE. The target system selected was Virtex 5 FPGA. Finally the design was downloaded onto the FPGA and the expected results were obtained. The device utilization summary for ECU is shown in fig 12. Fig 13 shows the experimental set up for Engine Control Unit showing the results of venting and isolation actions.

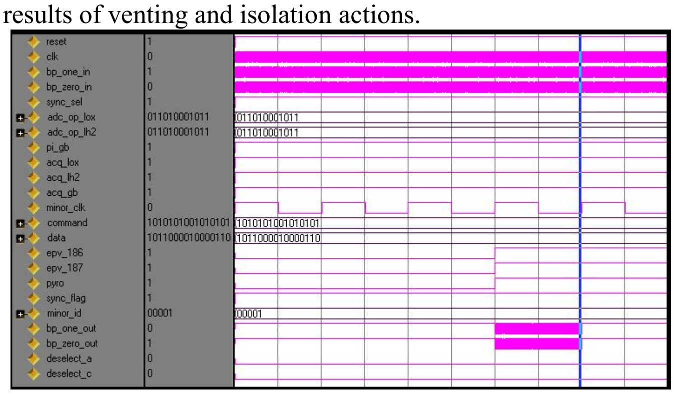

Fig 11: Simulated results for ECU.

Device Utilization Summary			
Logic Utilization	**Used**	**Available**	**Utilization**
Number of Slice Flip Flops	472	38,784	1%
Number of 4 input LUTs	971	38,784	2%
Logic Distribution			
Number of occupied Slices	625	19,392	3%
Number of Slices containing only related logic	625	625	100%
Number of Slices containing unrelated logic	0	625	0%
Total Number 4 input LUTs	1,054	38,784	2%
Number used as logic	971		
Number used as a route-thru	83		
Number of bonded IOBs	39	692	5%
IOB Flip Flops	3		
Number of PPC405s	0	2	0%
Number of GCLKs	3	16	18%
Number of GTs	0	12	0%
Number of GT10s	0	0	0%
Total equivalent gate count for design	10,778		
Additional JTAG gate count for IOBs	1,872		

Fig 12: Device utilization summary for ECU.

Fig 13: Experimental set up for ECU

V. CONCLUSION

The area of Cryogenic Rocket Engines is a vast one and new developments are being made in the field of Rocket Engineering. Due to the high specific impulse obtained during the ignition of fuels cryogenic engines are of much demand in the field of space exploration. The FPGA implementation of Cryo Pneumatic Engine Control offloads the processor. Thus the implementation reduces the complexity of the main processor and congestion in the communication channel thereby freeing the bandwidth of the channel. The system improves the computational margin. Using a specific algorithm makes the system more comprehensible for research works.

REFERENCES

[1] Wayne Wolf, "Embedded Computing" in *Computers as Components, Principles of Embedded Computing System Design,* 2nd ed.,Elsevier,Burlington,USA, 2008, pp 6-20.

[2] TullioCuatto et al," A Case Study in Embedded System Design: an Engine Control Unit," in *Design Automation Conference*, San Francisco, Califomia ,1998,804-807.

[3] Rakesh. R , Praveen. N and Prakash. E, "An Experimental Study of Cryogenic Engine," in *5th International Conference in Magna on Emerging Engineering Trends 2015 [ICMEET 2015]*, Volume 4, Special Issue 2, February 2015.

[4] Laurence de Quay and B. Keith Hodge, "A History of Collapse Factor Modeling and Empirical Data for Cryogenic Propellant Tanks," in *46th American Instititute of Aeronautics and Astronautics Joint Propulsion Conference and exhibit*, Nashvile ,TN, 2010,25-28.

[5] Hirohito Hosoda, Kazuyoshi Ohtsuka, Hideki Shimomura ,*A Microcomputer-Based System for Electronic EngineControl Unit Development*, IEEE Transactions On Industrial Electronics, Vol. 30, No. 2, May 1983.

[6] Jemti Jose."An FPGA Implementation of 1553 Protocol Controller".*International Journal of Computer Information Systems and Industrial Management Applications*, Volume 6, pp. 66 -76,2014.

[7] *MIL-STD-1553 Tutorial*, Condor Engineering, 1993-2000.